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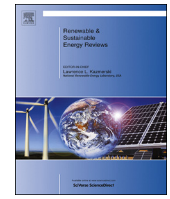

Assessment of theoretical near-shore wave power potential along the Lithuanian coast of the Baltic Sea

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ABSTRACT

Gradually increasing interest in utilisation of wave energy through development of wave energy converters is directing more attention to areas of lower energy potential, such as the Baltic Sea, compared to the oceans. In this paper, the theoretical wave power potential in the Lithuanian coast is evaluated using available multi-year visual observation data. A brief review of European wave energy resources, focusing more on semi-enclosed seas, is provided, as well as a comparison between wave energy potential and conventional hydropower potential in European countries. A conventional hydrological method, designed for calculating a distribution of annual hydrologic variables, was adopted to evaluate the design wave heights. Wave power flux values for monthly, seasonal and annual wave conditions were evaluated for high, median and low intensity years. In addition multi-year annual and seasonal wave power fluxes were calculated using scatter diagrams. The wave power flux for annual wave heights along the Lithuanian coast varies from 1.6 kW/m in a high intensity year to 0.4 kW/m in a low intensity year, which makes the near-shore wave power potential along the Lithuanian coast comparable with that of other European semi-enclosed seas.

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1. Introduction

Waves represent via wind a concentration of large quantities of solar power. Therefore, it is no coincidence that they have attracted attention as a renewable source for electricity generation. Prevailing western winds, together with the longest fetches, yielding the highest wind waves and the possibility of high swells, are reasons why the most suitable areas for wave energy generation in Europe are along the northern Atlantic coast. Consequently, the vast majority of innovations in wave energy converters (WECs) originate in the countries located in this area [1]. Europe's leading wave energy testing site – the European Marine Energy Centre, where pre-commercial WEC prototypes are tested – is also located in the northern Atlantic, in the Orkney Islands [2].

Wave energy resources in Europe are estimated to represent approximately 16% of the global total [3]. These resources were

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initially assessed at 92 GW [4]; this value was later revised to 320 GW [3,5]. This value was calculated without taking into consideration the Black Sea and the Baltic Sea [5], so presumably, the actual number is even greater.

Despite a natural interest in the areas of highest waves, in recent years there has been increased activity in assessments of wave energy potential in the European semi-enclosed seas, especially the Mediterranean Sea and the Black Sea. The wave energy resources in the Mediterranean Sea are estimated at 30 GW [5] with an average wave power flux of 5.8 kW/m [6]. The western coast of Sardinia, with a wave power flux approximately 10 kW/m in near-shore "hot spot" areas [7], along with the Sicily Channel, is the areas in the Mediterranean Sea with the highest wave energy potential [6]. Both of these areas are in Italy, therefore, the increasing activity from Italian scientists is unsurprising [6–9].

Other countries on the Mediterranean that are interested in electricity production from sea waves are Greece, Cyprus [10,11], Turkey [12] and Lebanon [13]. The Black Sea, which is especially relevant for Turkey, has also been analysed for its wave energy potential. A study of wave energy potential in the southeast coast of the Black Sea has revealed that area of Sinop Province has the highest potential, with an average wave power flux of 1.1 kW/m [14]. In the same year, two atlases of the Black Sea's wave energy resources, compiled using 13 [15] and 15 [16] years of hindcasted wave data, were published. It was found that the wave energy flux decreases along the coast from west to east and that average wave power flux in the Black Sea is 3 kW/m [15,16]. In addition, oscillating water column (OWC) and tapered channel system (TAPCHAN) WECs displayed good prospect to produce electricity on the western Black Sea coast, Eregli area [17].

The Baltic Sea is another European semi-enclosed sea. The Baltic Sea is connected to the North Atlantic through the North Sea by three shallow and narrow Danish Straits (the Øresund, the Great Belt and the Little Belt) via Kattegat and Skagerrak. The Baltic Sea is a shallow (average depth 55 m), brackish body of water [18]. The Baltic Sea's strategic position makes it one of the busiest economical areas of Europe and a possibly suitable place for the deployment and testing of WECs.

To date, Sweden has one of the biggest proficiency in the wave energy field in the Baltic Sea region [19–22]. An average annual wave power density map of the Baltic Sea, created using hindcasting calculation data of significant wave heights, has been published, and the average wave power flux in the Baltic Sea is estimated to range up to 4 kW/m. It was concluded that regardless of the technique chosen for wave energy utilisation in the Baltic Sea, the amount of total energy will vary locally depending on a number of factors, particularly fetch, making the leeward coast less interesting [20].

Prevailing western winds and long fetches make the eastern coast of the Baltic Sea a potentially attractive area for wave energy conversion. Still, the amount of relevant scientific works in this region so far is very scarce. Initial estimations were recently published by the Estonian scientists: it was found that in the 10–20 m depth along the coast of Latvia and the western Estonian archipelago, the wave power flux can be up to 2.5–4 kW/m [23,24].

The available estimations of wave energy resources in European countries (Fig. 1) only confirm that the major part of these resources is situated in the north Atlantic region, followed by the North Sea and the semi-enclosed seas. In Fig. 1, a comparison is made between the potential for wave energy and the technically feasible potential for conventional hydro power (without environmental constraints and including installed capacity). The trend for conventional hydro is completely different and partially explains why, for example, UK, Ireland and Denmark are so interested in wave energy. On the other hand, Sweden and France are already among the European countries with the greatest production of

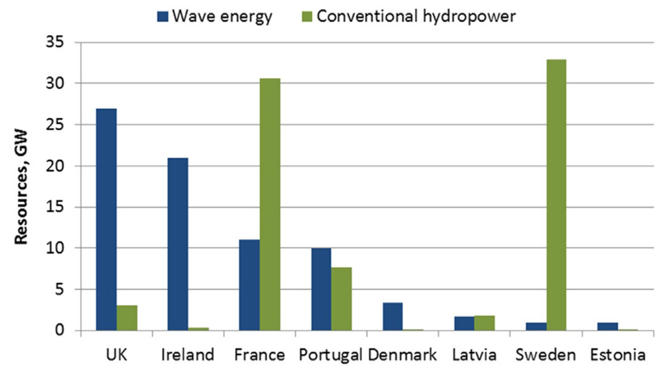

Fig. 1. Wave energy and conventional hydropower resources in European countries according to data from [4,7,23,25–27].

Table 1
National targets for wave and tidal energy for 2020 and installed capacity of wave energy in EU Member States.

EU member state	National targets for 2020 (NREAPs) (MW) [27]	National targets for 2020 (EU-OEA) (MW) [28]	Installed capacity in 2012 (IEA-OES) (kW) [29]
UK	1300	2000	4340
France	380	800	n/a
Ireland	75	500	n/a
Denmark	0	500	250
Portugal	250	300	700
Spain	100	n/a	296
Sweden	0	n/a	150
Italy	3	n/a	n/a

electricity using conventional hydro power plants, and the construction of new plants is limited by environmental restrictions, so their interest in wave energy will presumably continue to grow. In Portugal and Latvia, however, the potentials for both types of energy are relatively equal.

To obtain the whole picture of European wave energy resources, two more countries that have extensive wave energy resources and are missing in Fig. 1, Spain and Norway, need to be mentioned. The northern part of Spain is in the northern Atlantic region and, judging by the latest studies, has a great potential for wave energy. The offshore annual wave power flux in the Death Coast can reach 50 kW/m [28], while in the Bay of Biscay it can exceed 30 kW/m [29]. Furthermore, Norway was one of the pioneering countries in the European wave energy sector [5,30]. The average offshore wave power flux along the Norwegian coast is 20–40 kW/m [31].

Islands are the areas, where energy utilisation from waves can play a major role in the future [32]. All related studies [33–35] mention that electricity generation there is expensive and dependable on mainland sources, therefore, waves can provide the solution, as islands mainly are located in open areas, suitable for occurrence of high waves and consequently efficient generation of electricity. The islands in the European semi-enclosed seas, that are considered as areas for electricity generation, are Sardinia [7] and Cyprus [10,11] in the Mediterranean Sea and Åland [21] in the Baltic Sea.

It is assumed that European ocean energy generation has the potential to reach 3.6 GW of installed capacity by 2020 [25]. Table 1 presents the national targets for wave and tidal energy for 2020, outlined by the national renewable energy action plans (NREAPs) of European Union Member States [36]; the national targets for ocean energy in Europe for 2020, outlined by the European Ocean Energy Association (EU-OEA) [37]; and the installed capacity of wave power in 2012, outlined by Ocean

Energy Systems (IEA-OES) [38]. It appears that national targets have thus far only been set by the countries whose coasts provide extensive wave energy resources.

The main aim of this study is to assess the wave energy potential in the Lithuanian near-shore area using frequency analysis of multi-year observed visual wave height data. The overall objectives of the study are:

- to estimate the design years' wave heights using probability distribution analysis and conventional hydrological method;
- to assess the theoretical wave power potential using the design years' monthly, seasonal and average wave heights; and
- to assess the theoretical wave power potential using annual and seasonal scatter diagrams.

2. Methodology

2.1. Visual observations

Wave monitoring along the Lithuanian coastline has taken place since the middle of the 20th century. These measurements were part of the Eastern Baltic Sea coastline marine monitoring launched by former Soviet Union's hydrometeorological service. Until 2011, wave heights and periods along the Lithuanian coast were measured only visually or by using various forms of perspectometers. Perspectometers are optical rangefinders adopted for remote wave observations. When these perspectometers were used for data collection, the observations were indicated as half-instrumental. Currently, visual observations along the Lithuanian coast are still carried out in Nida and Klaipėda (Table 2).

Depending on the season, visual observations of average wave heights, maximum wave heights and wave periods are performed one, two or three times during daylight hours (6:00; 12:00 and 18:00 GMT). Lithuanian coastal wave gauging stations were upgraded in 2011. Bottom-mounted wave recorders based on silicon pressure sensors were installed in Palanga and Klaipėda (Table 2). Instrumentally measured data were not used for wave energy assessments in this paper due to the short time span of the records and recurring device calibration errors. The complete visual and instrumental coastal observation network in Lithuania is presented in Fig. 2.

2.2. Assessment of wave power potential

In this paper, visual observation data from the Klaipėda wave gauging station were used. The Klaipėda wave gauge is located slightly more than 200 m north of the northern breakwater of the port of Klaipėda, approximately 3 m above the mean water level. Waves are observed approximately 500 m out to sea at the depth $h = 6$ m.

Table 2
Coastal hydrometeorological stations in Lithuania.

Waves gauging station	Type of observations	Measurements and available data
Šventoji	Visual	1945–1946, 1948–1958, 1965–1968
	Instrumental	n/a
Palanga	Visual	1993–2011
	Instrumental	2011–present
Klaipėda	Visual	1948–present
	Instrumental	2011–present
Nida	Visual	1947–1961, 1972–present
	Instrumental	n/a

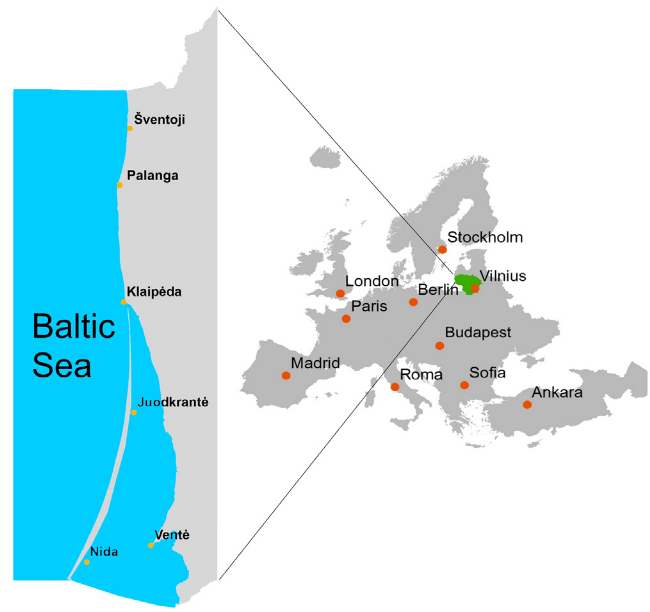

Fig. 2. Network of Lithuanian coastal hydrometeorological stations used for wave monitoring.

Table 3
Examination of deep water definition in Klaipėda coastal observation site.

Characteristic sea state and representative year	Annual wave height (m)	Typical wave period T, (s)	Wavelength (linear Eq.), (m) ($\lambda = gT^2/2\pi$)	Deep water condition $h \geq \lambda/2$
High intensity (1973/74)	0.89	4.2	27.6	$6 \geq 13.8$
Median intensity (1994/95)	0.67	3.5	19.1	$6 \geq 9.6$
Low intensity (1976/77)	0.53	3.1	15.0	$6 \geq 7.5$

First, before calculating the wave power flux at the described observation site, the deep water conditions were examined. For this step, the annual average wave heights for the design years and typical values of these waves' periods were used (Table 3).

As Table 3 suggests, waves at the Klaipėda visual observation point are beginning to shoal. Still, at this depth, intermediate water conditions ($\lambda/2 > h \geq \lambda/20$) are valid for all three cases, and linear wave theory does rather well in these conditions [39].

It is also important to determine how visually measured wave heights and periods correspond to those used in wave power flux equations for irregular waves. This is rather easy with wave height observations. Many references have stated that visually measured wave heights correspond well with significant wave heights [40–43]. However, visually measured wave periods remain controversial. Though it is generally accepted that these measurements are much less accurate, for a long time, observed wave periods were assumed to correspond to zero-crossing periods [44]. Recently, it has been found that visually observed periods correspond more closely to the peak period [45] and are related to the zero-crossing period by the following equation:

$$T_p = 1.4T_z, \tag{1}$$

where T_p is the peak period and T_z is the zero-crossing period.

The observer of any coastal observation station is taught to spot the highest waves. However, to fix a zero level during observations is difficult. Consequently, by only measuring the periods of higher

waves, observers calculate a wave period that corresponds more accurately to the peak period than to the zero-crossing period. Therefore, in this study we assumed that the visually measured wave height and period correspond to the significant wave height H_s, which, in turn, is assumingly equal to the corresponding spectral estimation of H_s, normally denoted as H_{m0} and the peak period T_p, which, in turn, corresponds to the frequency where the spectral density $S(f)$ is maximum. This enables to calculate wave power flux from the wave spectrum [46]:

$$P = \rho g \int_0^{\infty} S(f) c_g(f) df, \tag{2}$$

where ρ is the mass density of water (in this case, the brackish water of the Baltic Sea was used, with a density of 1010 kg/m^3 [18]), g is the gravitational constant (9.81 m/s^2), $S(f)$ is the spectral density and c_g is the group velocity. The equation of the group velocity in intermediate water is

$$c_g(f) = \frac{c}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right], \tag{3}$$

where k is the wave number and c is the phase velocity. Their equations are

$$k(f) = \frac{2\pi}{\lambda}, \tag{4}$$

and

$$c(f) = \frac{gT}{2\pi}\tanh(kh), \tag{5}$$

where λ is the wavelength and T is the wave period. The equation for wavelength in intermediate water is

$$\lambda(f) = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{\lambda}\right), \tag{6}$$

In Eq. (6), λ is on both sides of the equality. The equation therefore must be solved by using a graphic or iterative technique.

Table 4
Visually measured wave periods for corresponding wave heights along the Klaipėda coast.

H_s (m)	0.4	0.6	0.8	1.0	1.2	1.4	1.6
T_p (s)	3.1	3.2	4.1	4.5	4.9	5.1	5.6

The first step in estimating the wave power flux in our case was to determine which wave energy spectrum is best suited for the Baltic Sea wave states. Earlier studies have suggested the applicability of the JONSWAP spectrum [47]. The parameterised JONSWAP wave spectrum modified for the Baltic Sea is used in this study [48]

$$S(f) = K_m \frac{H_s^2 T_p}{(T_p f)^5} \exp\left[-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right] \gamma^{\beta}, \tag{7}$$

where K_m is an empirically determined constant (0.1786), H_s is the significant wave height, T_p is the peak wave period, f_p is the peak frequency, f is the wave frequency and γ is the peak enhancement factor (4.0)

$$\beta = \exp\left(-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right),$$

$$\sigma = 0.07 \text{ for } f \le f_p, \sigma = 0.09 \text{ for } f > f_p. \tag{8}$$

where σ is the shape parameter.

The visually measured wave periods corresponding to visually measured wave heights that were used for wave power flux calculations are presented in Table 4.

The same data set of average monthly and average annual wave heights from 1970–2010 from the Klaipėda wave gauging station was used to assess near-shore wave power potential using probability distributions analysis, conventional hydrological method and scatter diagrams. The chosen intervals for scatter diagrams are: H_s −0.2 m and T_p −0.5 s. Maximum and minimum values of intervals are selected so that all data fall within the following range.

3. Results and discussions

3.1. Probability distributions of wave heights

The goal of probability distribution analysis was to reveal a probability distribution that best fits the average annual wave heights in the near-shore coastal area of Klaipėda, Lithuania. To establish best fit, the observed visual wave height data from 1970 to 2010 from the Klaipėda wave gauging station were used. It was not possible to use a longer data set because before 1970 no average wave heights were noted in the coastal observations

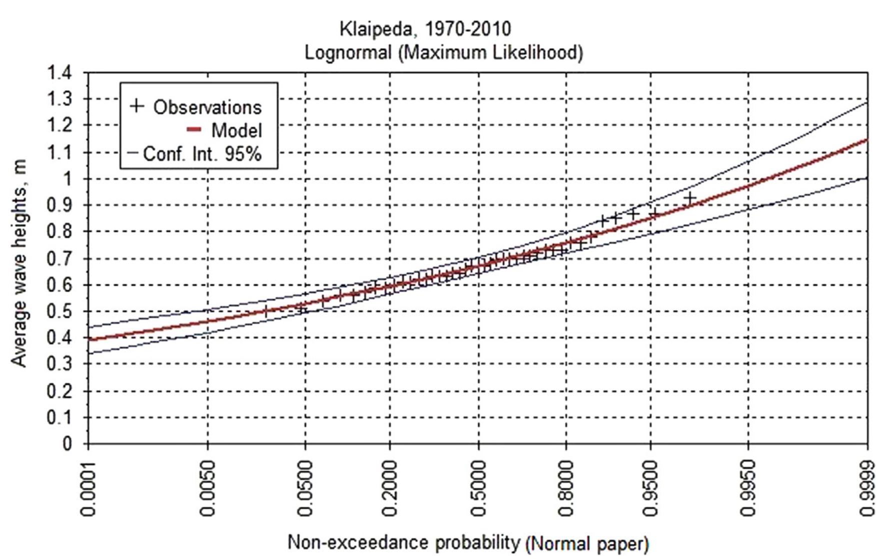

Fig. 3. Lognormal distribution of average annual wave heights along the coast of Klaipėda.

register for waves lower than 0.5 m. Therefore, it is not possible to calculate average annual wave heights.

The software Hyfran [49], developed in the University of Quebec, Canada by Dr. Bernard Bobée, was used to determine all applicable probability distributions for average annual wave heights in the Lithuanian near-shore conditions. In this case, for distribution estimation, the maximum likelihood method was used. Fitting was obtained by applying the chi-square test. The Hyfran programme verified the adequacy of fit by accepting or rejecting the null hypothesis: the underlying distribution of the sample according to the chi-square test result fits the theoretical distribution. The best fit was gained according to the Akaike information criterion (AIC) and the Bayesian information criterion (BIC).

All obtained values yielding the best fit for a lognormal distribution (Fig. 3) are as follows: chi-square statistics 4.5, degrees of freedom 5, p-Value 0.48, AIC criterion -72.1 and BIC criterion -68.7. The calculated average annual wave heights along the coast of Klaipėda, depending on the probability and return period, are presented in Table 5. An in-depth probability distribution analysis of wave heights and wind speeds along the coast of Klaipėda was published in 2012 [50].

3.2. Conventional hydrological method

A conventional hydrological method designed for calculating a distribution of annual hydrologic variables using multi-year data was applied to test the results of the probability distribution analysis. This method consists of several basic steps. The first is to calculate monthly average wave heights (Table 6).

The second step is to determine seasonal average wave heights and to arrange them by water year (term, starting from March and ending at next year's February) and seasonal values in descending order, while also calculating the probability for each ranked year (Table 7). The probability is computed using the Weibull equation [51]

$$P=\frac{m}{n+1}100\%, \quad (9)$$

where m is the rank number and n is the number of ranked years.

From Table 7, statistically ranked years with the closest probabilities to the chosen design years (high, median and low intensity) are selected (Table 8) to test the results of probability distribution analysis and to assess the theoretical wave power potential.

Average monthly wave heights of the whole data set are juxtaposed with monthly average wave heights gained from selected high, median and low intensity years in Fig. 4.

The line of the average monthly wave heights for the whole 41-year data set can be taken as a benchmark. This line reflects not only typical values of average wave heights along the Lithuanian coast of the Baltic Sea but also their seasonal variations. In contrast, the variations of monthly average wave heights in design years are higher, but this is due to natural causes.

Average annual wave heights obtained for the design years by applying a lognormal distribution (5% -0.85 m; 50% -0.67 m and 95% -0.53 m) are similar to those that were obtained by applying conventional hydrological method (5% -0.89 m; 50% -0.67 m; 95% -0.53 m). Therefore, it can be concluded that the conventional hydrological method is a simple and practical method for the analysis of wave height observation data. Consequently, average wave height values gained by using this method are used in this paper for theoretical wave power assessment along the Lithuanian coast of the Baltic Sea, in the Klaipėda near-shore area.

3.3. Wave power potential

The wave power flux values obtained for average monthly waves of low, median and high intensity years are presented in Fig. 5. In addition, the seasonal and annual average wave power fluxes for design years are shown in Table 9.

The scatter diagrams calculated using monthly average wave heights and showing annual and seasonal probabilities of occurrence of sea states together with theoretical power flux distribution through all these wave states are presented in Figs. 6 and 7.

The varying results of estimated wave power flux using two different methods do not dispute, but complement each other. From design years' wave power flux estimations it becomes clear that in the high intensity wave year average wave power flux can be 1.6 kW/m, while seasonal wave power flux can be even higher depending on natural causes. The average multi-year power flux in

Table 5
Average wave heights along the coast of Klaipėda based on lognormal distribution.

Characteristic sea state for the year	Probability, P (%)	Return period, T_r (years)	Average wave height (m)
Very high intensity	1	100	0.94
High intensity	5	20	0.85
Medium intensity	25	4	0.74
Median intensity	50	2	0.67
Medium low intensity	75	4	0.61
Low intensity	95	20	0.53
Very low intensity	99	100	0.48

Table 6
Monthly average wave heights along the coast of Klaipėda (m).

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	0.65	0.43	0.81	0.95	0.54	0.55	1.06	0.58	1.24	1.10	1.27	0.89
1971	1.01	0.94	0.68	0.55	0.36	0.54	0.69	0.74	0.72	1.47	1.51	1.28
1972	0.35	0.36	0.76	0.71	0.49	0.48	0.53	0.82	0.62	1.11	1.68	0.96
1973	0.68	0.89	0.68	0.85	0.58	0.74	0.68	0.81	1.09	1.00	1.66	1.24
1974	0.82	0.57	0.45	0.54	0.64	0.61	1.08	0.53	0.78	0.90	0.96	1.27
…	…	…	…	…	…	…	…	…	…	…	…	…
2006	0.45	0.43	0.47	0.42	0.49	0.41	0.33	0.41	0.59	0.68	0.82	1.22
2007	1.62	0.51	0.54	0.60	0.34	0.52	0.64	0.63	0.68	0.54	0.96	0.82
2008	0.93	1.05	0.62	0.33	0.34	0.54	0.43	0.73	0.40	1.13	0.99	0.60
2009	0.71	0.46	0.52	0.39	0.58	0.57	0.54	0.59	0.89	0.83	0.74	0.55
2010	0.46	0.35	0.58	0.44	0.42	0.46	0.38	0.60	0.67	0.65	0.59	0.56

Table 7
Water year and seasonal wave heights values (m) in descending order along the coast of Klaipėda.

No. in descending order	*P* (%)	Water year (March–February)		Spring (March–May)		Summer (June–August)		Autumn (September–November)		Winter (December–February)	
		Year	Aver. wave height	Year	Aver. wave height	Year	Aver. wave height	Year	Aver. wave height	Year	Aver. wave height
1	2.4	1970/71	0.91	1970/71	0.97	2000/01	0.80	1973/74	1.25	1975/76	1.29
2	4.9	1973/74	0.89	1973/74	0.94	1973/74	0.74	1983/84	1.24	1999/00	1.22
3	7.3	1975/76	0.84	1975/76	0.93	1974/75	0.74	1971/72	1.23	1980/81	1.12
4	9.8	1983/84	0.82	1983/84	0.89	1970/71	0.73	1970/71	1.20	2006/07	1.12
5	12.2	1972/73	0.81	1972/73	0.88	1979/80	0.73	1978/79	1.15	1974/75	1.07
…	…	…	…	…	…	…	…	…	…	…	…
36	87.8	1984/85	0.54	1976/77	0.55	1996/97	0.46	1995/96	0.58	1978/79	0.50
37	90.2	1993/94	0.54	1984/85	0.55	1992/93	0.45	1996/97	0.57	1984/85	0.50
38	92.7	1976/77	0.53	1995/96	0.53	1995/96	0.43	1976/77	0.56	2005/06	0.48
39	95.1	2005/06	0.51	1993/94	0.52	1997/98	0.41	2005/06	0.56	2009/10	0.45
40	97.6	1995/96	0.51	2005/06	0.49	2006/07	0.38	1993/94	0.42	1995/96	0.42

Table 8
Average wave heights for design years along the coast of Klaipėda.

Characteristic sea state for the year	Average wave heights (m)																
	Monthly												Seasonal				Annual
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Spr	Sum	Aut	Win	
High intensity (1973/74)	0.68	0.85	0.58	0.74	0.68	0.81	1.09	1.00	1.66	1.24	0.82	0.57	0.70	0.74	1.25	0.88	0.89
Median intensity (1994/95)	0.83	0.40	0.45	0.77	0.36	0.51	0.62	0.69	0.85	0.77	0.71	1.07	0.56	0.55	0.72	0.85	0.67
Low intensity (1976/77)	0.68	0.62	0.41	0.58	0.48	0.38	0.58	0.52	0.57	0.60	0.46	0.49	0.57	0.48	0.56	0.52	0.53

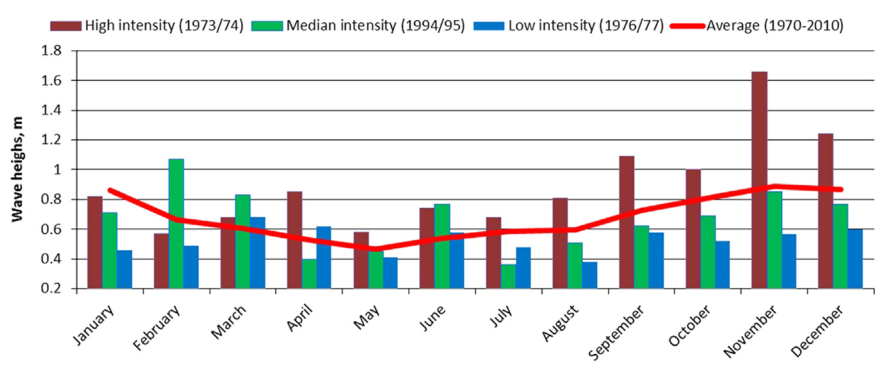

Fig. 4. Average wave heights along the coast of Klaipėda.

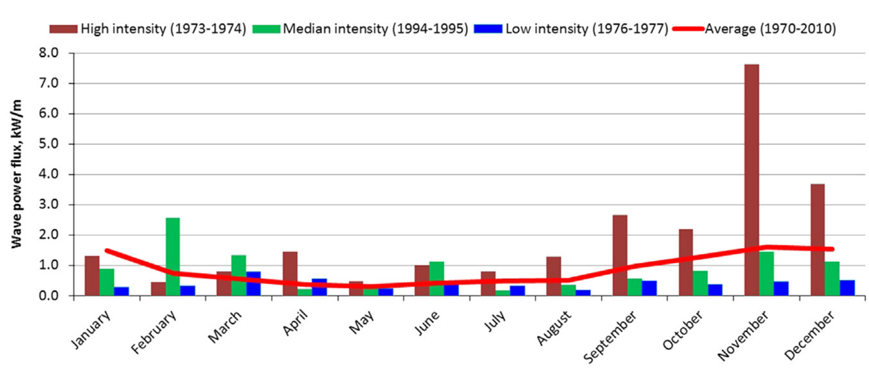

Fig. 5. Wave power flux of average monthly waves along the coast of Klaipėda.

Table 9
Seasonal and annual average wave power fluxes along the coast of Klaipėda.

Characteristic sea state and representative year	Average wave power flux (kW/m)				
	Spring	Summer	Autumn	Winter	Annual
High intensity (1973/74)	0.87	1.00	3.75	1.56	1.60
Median intensity (1994/95)	0.44	0.43	0.95	1.45	0.72
Low intensity (1976/77)	0.46	0.31	0.44	0.37	0.38

Annual	T_p (s)								
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
H_s (m)	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.20	***0.20***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.61	***0.61***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	1.63	0.00	***1.63***
	1.2-1.4	0.00	0.00	0.00	0.00	3.25	0.41	0.00	***3.66***
	1.0-1.2	0.00	0.00	0.00	1.22	5.89	0.00	0.00	***7.11***
	0.8-1.0	0.00	0.00	0.00	13.21	0.00	0.00	0.00	***13.21***
	0.6-0.8	0.00	6.50	13.62	2.44	0.00	0.00	0.00	***22.56***
	0.4-0.6	0.00	40.45	0.00	0.00	0.00	0.00	0.00	***40.45***
	0.2-0.4	5.28	5.28	0.00	0.00	0.00	0.00	0.00	***10.57***
	Total	***5.28***	***52.24***	***13.62***	***16.87***	***9.15***	***2.03***	***0.81***	***100.00***

Annual	T_p (s)								
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
H_s (m)	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.02	***0.02***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.05	***0.05***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.09	0.00	***0.09***
	1.2-1.4	0.00	0.00	0.00	0.00	0.13	0.02	0.00	***0.15***
	1.0-1.2	0.00	0.00	0.00	0.03	0.17	0.00	0.00	***0.20***
	0.8-1.0	0.00	0.00	0.00	0.22	0.00	0.00	0.00	***0.22***
	0.6-0.8	0.00	0.05	0.12	0.02	0.00	0.00	0.00	***0.19***
	0.4-0.6	0.00	0.15	0.00	0.00	0.00	0.00	0.00	***0.15***
	0.2-0.4	0.01	0.01	0.00	0.00	0.00	0.00	0.00	***0.01***
	Total	***0.01***	***0.20***	***0.12***	***0.27***	***0.29***	***0.11***	***0.07***	***1.07***

Fig. 6. Annual theoretical wave power flux (kW/m) calculation depending on probability of occurrence (%) of sea states.

median year is approximately 0.7 kW/m. Still, conventional hydrological method does not show the distribution of energy for different wave heights and wave periods. According to scatter diagrams, that enable this, wave climate along the Lithuanian coast can be divided into two seasons: spring–summer and autumn–winter with power fluxes 0.50–0.58 and 1.59–1.60 kW/m, respectively. Most energetic sea states have T_p of 4–4.5 s and H_s of 0.8–1.0 m, while the most frequent wave heights have T_p of 3–3.5 s and H_s 0.4–0.6 m. Authors acknowledge the bias resulting from calculating the wave power flux from averaged visual measured wave heights.

The Baltic Sea cannot compete with the North Atlantic in terms of wave power flux values. The Baltic Sea has an advantage as a relatively small and enclosed water body, dependent on local winds for wave generation, which makes it more predictable. In addition, because it is less salty and has smaller storms than the ocean, the Baltic Sea is a less hazardous environment which makes it more economically feasible. Judging by Fig. 5 and Table 9, the wave energy flux along the coast of Klaipėda during the cold period of the year, when energy is most needed, can reach 2 kW/m or more.

4. Conclusions

The increasing interest in the wave power potential of the Mediterranean Sea and the Black Sea leaves the Baltic Sea more of a “blank spot” in the European wave energy map. In this paper, multi-year statistical wave visual observation data are used to assess the near-shore wave power potential in the Klaipėda coastal area in the eastern Baltic Sea.

Annual average wave heights were obtained using probability distribution analysis and were similar or identical to those obtained using a conventional hydrological method. Consequently, the conventional hydrological method was used for theoretical wave energy evaluations using visual wave observation data. Still, one detriment of this method is that the monthly and seasonal wave energy values calculated using this method can be misleading. It is thus important to recognise extreme high or low average monthly wave height values that may occur in a selected design year.

Average annual wave heights along the Klaipėda coast at 6 m depth for each design year are as follows: high intensity – 0.89 m, median intensity – 0.67 m, and low intensity – 0.53 m. The wave power flux of the average annual wave heights is, respectively, 1.60 kW/m, 0.72 kW/m and 0.38 kW/m. Average annual wave power flux calculated using scatter diagrams is 1.07 kW/m. These theoretical wave power flux values indicate that wave power along the Lithuanian coast of the Baltic Sea is comparable with other European semi-enclosed seas. Therefore, the assessment of the Baltic Sea's wave power potential will continue, and the next step will be numerical modelling of near-shore wave energy potential along the Lithuanian coast.

Winter		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.81	***0.81***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.81	***0.81***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	2.44	0.00	***2.44***
	1.2-1.4	0.00	0.00	0.00	0.00	8.13	1.63	0.00	***9.76***
H_s (m)	1.0-1.2	0.00	0.00	0.00	2.44	11.38	0.00	0.00	***13.82***
	0.8-1.0	0.00	0.00	0.00	15.45	0.00	0.00	0.00	***15.45***
	0.6-0.8	0.00	2.44	15.45	3.25	0.00	0.00	0.00	***21.14***
	0.4-0.6	0.00	26.02	0.00	0.00	0.00	0.00	0.00	***26.02***
	0.2-0.4	5.69	4.07	0.00	0.00	0.00	0.00	0.00	***9.76***
	Total	***5.69***	***32.52***	***15.45***	***21.14***	***19.51***	***4.07***	***1.63***	***100.00***

Winter		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.08	***0.08***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.07	***0.07***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.14	0.00	***0.14***
	1.2-1.4	0.00	0.00	0.00	0.00	0.32	0.07	0.00	***0.39***
Hs (m)	1.0-1.2	0.00	0.00	0.00	0.06	0.32	0.00	0.00	***0.38***
	0.8-1.0	0.00	0.00	0.00	0.26	0.00	0.00	0.00	***0.26***
	0.6-0.8	0.00	0.02	0.13	0.03	0.00	0.00	0.00	***0.18***
	0.4-0.6	0.00	0.09	0.00	0.00	0.00	0.00	0.00	***0.09***
	0.2-0.4	0.01	0.01	0.00	0.00	0.00	0.00	0.00	***0.01***
	Total	***0.01***	***0.12***	***0.13***	***0.35***	***0.64***	***0.21***	***0.15***	***1.60***

Spring		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.2-1.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
H_s (m)	1.0-1.2	0.00	0.00	0.00	0.00	0.81	0.00	0.00	***0.81***
	0.8-1.0	0.00	0.00	0.00	5.69	0.00	0.00	0.00	***5.69***
	0.6-0.8	0.00	6.50	10.57	3.25	0.00	0.00	0.00	***20.33***
	0.4-0.6	0.00	54.47	0.00	0.00	0.00	0.00	0.00	***54.47***
	0.2-0.4	9.76	8.94	0.00	0.00	0.00	0.00	0.00	***18.70***
	Total	***9.76***	***69.92***	***10.57***	***8.94***	***0.81***	***0.00***	***0.00***	***100.00***

Spring		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.2-1.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
H_s (m)	1.0-1.2	0.00	0.00	0.00	0.00	0.02	0.00	0.00	***0.02***
	0.8-1.0	0.00	0.00	0.00	0.09	0.00	0.00	0.00	***0.09***
	0.6-0.8	0.00	0.05	0.09	0.03	0.00	0.00	0.00	***0.17***
	0.4-0.6	0.00	0.20	0.00	0.00	0.00	0.00	0.00	***0.20***
	0.2-0.4	0.01	0.01	0.00	0.00	0.00	0.00	0.00	***0.02***
	Total	***0.01***	***0.25***	***0.09***	***0.13***	***0.02***	***0.00***	***0.00***	***0.50***

Summer		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.2-1.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
H_s (m)	1.0-1.2	0.00	0.00	0.00	0.00	2.44	0.00	0.00	***2.44***
	0.8-1.0	0.00	0.00	0.00	5.69	0.00	0.00	0.00	***5.69***
	0.6-0.8	0.00	9.76	13.82	1.63	0.00	0.00	0.00	***25.20***
	0.4-0.6	0.00	56.10	0.00	0.00	0.00	0.00	0.00	***56.10***
	0.2-0.4	4.88	5.69	0.00	0.00	0.00	0.00	0.00	***10.57***
	Total	***4.88***	***71.54***	***13.82***	***7.32***	***2.44***	***0.00***	***0.00***	***100.00***

Summer		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.2-1.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
H_s (m)	1.0-1.2	0.00	0.00	0.00	0.00	0.07	0.00	0.00	***0.07***
	0.8-1.0	0.00	0.00	0.00	0.09	0.00	0.00	0.00	***0.09***
	0.6-0.8	0.00	0.07	0.12	0.02	0.00	0.00	0.00	***0.20***
	0.4-0.6	0.00	0.20	0.00	0.00	0.00	0.00	0.00	***0.20***
	0.2-0.4	0.01	0.01	0.00	0.00	0.00	0.00	0.00	***0.01***
	Total	***0.01***	***0.28***	***0.12***	***0.11***	***0.07***	***0.00***	***0.00***	***0.58***

Autumn		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	1.63	***1.63***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	4.07	0.00	***4.07***
	1.2-1.4	0.00	0.00	0.00	0.00	4.88	0.00	0.00	***4.88***
H_s (m)	1.0-1.2	0.00	0.00	0.00	2.44	8.94	0.00	0.00	***11.38***
	0.8-1.0	0.00	0.00	0.00	26.02	0.00	0.00	0.00	***26.02***
	0.6-0.8	0.00	7.32	14.63	1.63	0.00	0.00	0.00	***23.58***
	0.4-0.6	0.00	25.20	0.00	0.00	0.00	0.00	0.00	***25.20***
	0.2-0.4	0.81	2.44	0.00	0.00	0.00	0.00	0.00	***3.25***
	Total	***0.81***	***34.96***	***14.63***	***30.08***	***13.82***	***4.07***	***1.63***	***100.00***

Autumn		T_p (s)							
		2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	*Total*
	1.8-2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	1.6-1.8	0.00	0.00	0.00	0.00	0.00	0.00	0.13	***0.13***
	1.4-1.6	0.00	0.00	0.00	0.00	0.00	0.24	0.00	***0.24***
	1.2-1.4	0.00	0.00	0.00	0.00	0.19	0.00	0.00	***0.19***
H_s (m)	1.0-1.2	0.00	0.00	0.00	0.06	0.25	0.00	0.00	***0.31***
	0.8-1.0	0.00	0.00	0.00	0.43	0.00	0.00	0.00	***0.43***
	0.6-0.8	0.00	0.05	0.13	0.02	0.00	0.00	0.00	***0.19***
	0.4-0.6	0.00	0.09	0.00	0.00	0.00	0.00	0.00	***0.09***
	0.2-0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
	Total	***0.00***	***0.15***	***0.13***	***0.51***	***0.44***	***0.24***	***0.13***	***1.59***

Fig. 7. Seasonal theoretical wave power flux (kW/m) calculation depending on probability of occurrence (%) of sea states.

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